Suppression of diffraction in DIS on nuclei and dynamical mechanism of leading twist nuclear shadowing

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Based on Guzey, Strikman, JHEP 07 (2024) 045 [2403.08342 [hep-ph]]

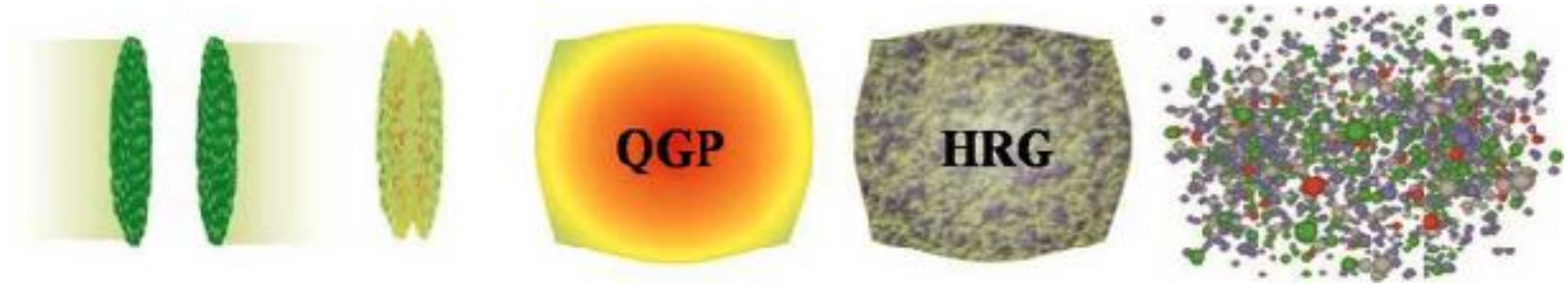
Outline:

- Introduction and motivation: nuclear shadowing vs. saturation
- Leading twist approach (LTA) as a dynamical mechanism of nuclear shadowing (NS) and its predictions for diffraction in DIS on nuclei
- LTA and nuclear (non-enhancement) of the saturation scale
- Summary

Nuclear shadowing

- Nuclear shadowing (NS) is general phenomenon of high-energy scattering → nuclear cross section < sum of nucleon cross sections.

- NS suppresses nuclear structure functions & parton distributions at small x:
  - fundamental in perturbative QCD
  - define initial conditions (cold nuclear matter effects) in pA & AA scattering.



Initial State

Pre-equilibrium

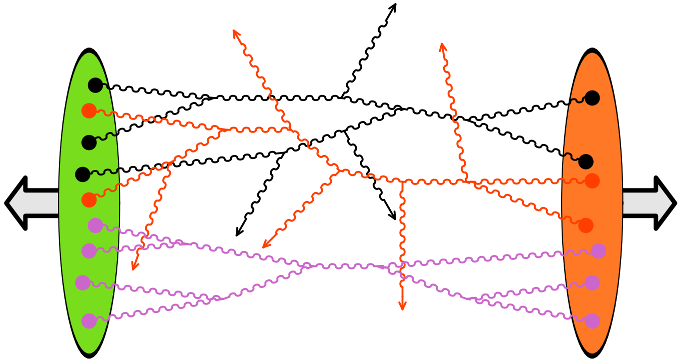
Hydro-expansion of QGP or hadron gas

Hadronization

Freeze-out

S. Bass,
Duke Univ.

- NS affects description of gluon-rich nuclear matter in quark-gluon color glass condensate (CGC) framework.

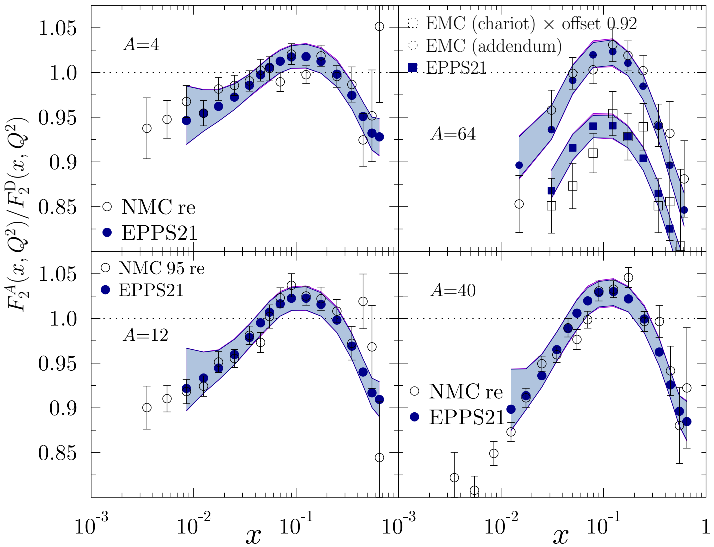


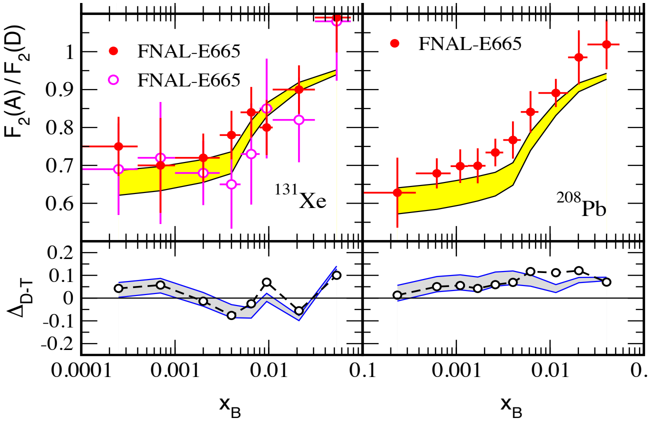
F. Gelis, 1412.0471 [hep-ph]

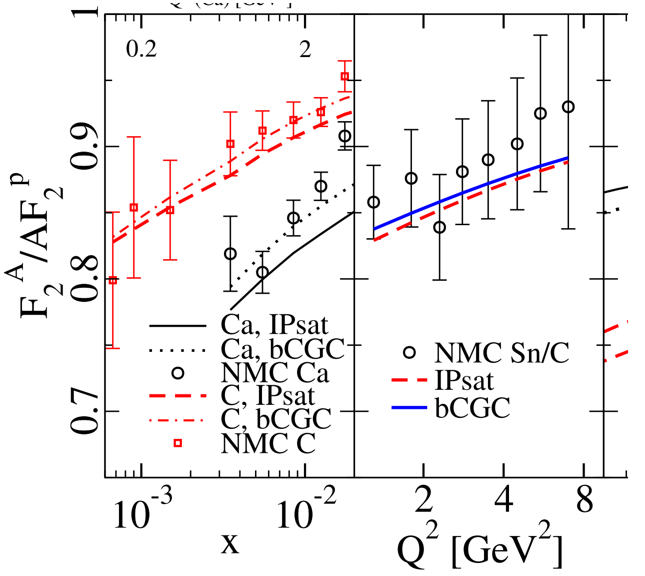
Dynamical mechanism of nuclear shadowing

- Cleanest way to probe nuclear shadowing → nuclear deep inelastic scattering (DIS) → ratio of nucleus/proton structure functions F_2^A/F_2^p.

- Same fixed-target data can be described by different mechanisms of NS:
  - leading-twist nuclear PDFs from global QCD fits, Eskola, Paakkinen, Paukkunen, Salgado, EPJC 82 (2022) 5, 413 (EPPS21); Klasen, Paukkunen, 2311.00450 [hep-ph]
  - nucleus-enhanced power (higher-twist) corrections, Qiu, Vitev, PRL 93 (2004) 262301
  - mixture of leading and higher twist effects in dipole model with gluon saturation, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303





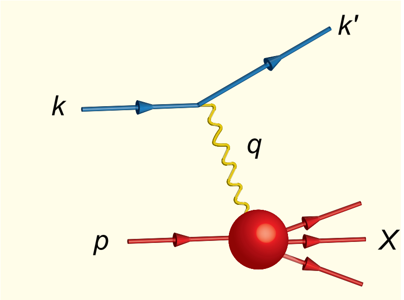


- Outstanding questions: What is the mechanism/origin of this suppression? What is the relation between shadowing and saturation?

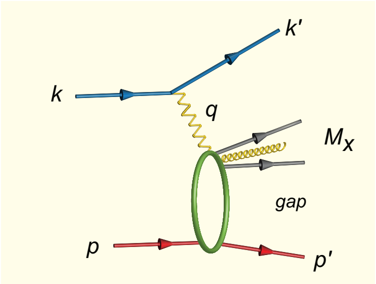
Diffraction in DIS on nuclei

- The planned Electron-Ion Collider (EIC) in USA has potential to discriminate among approaches of NS due to:
    - wide $x - Q^2$ coverage
    - measurement of longitudinal structure function $F_L^A(x, Q^2)$ sensitive to gluons
    - for the first time measurement of hard diffraction in nuclear DIS.

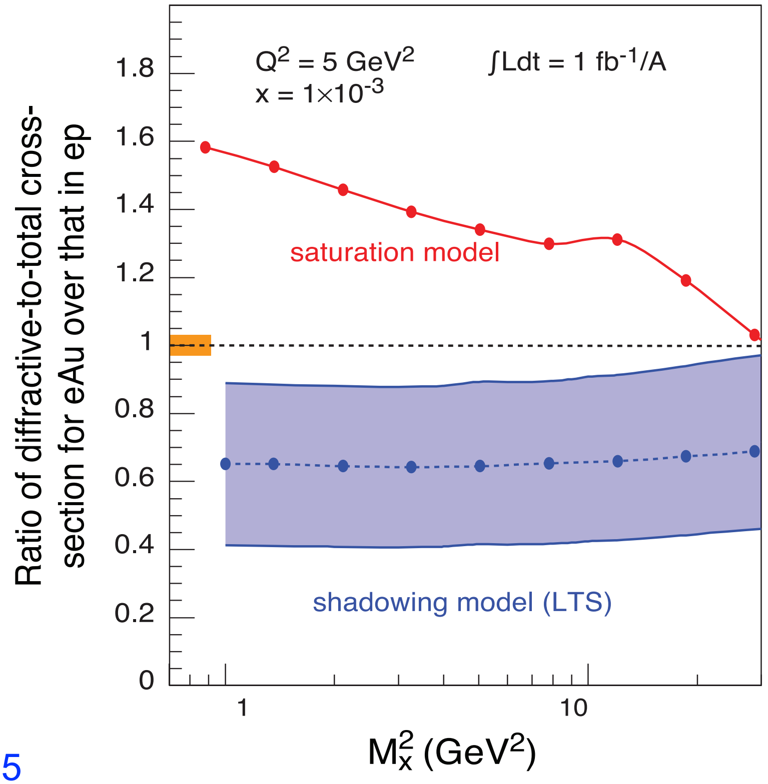
- Sensitive observable is the ratio of diffractive to total DIS cross sections for a heavy nucleus and the proton, Accardi et al., EPJ A52 (2016) 9, 268 [1212.1701 [hep-ex]]:



Total DIS



Diffractive DIS



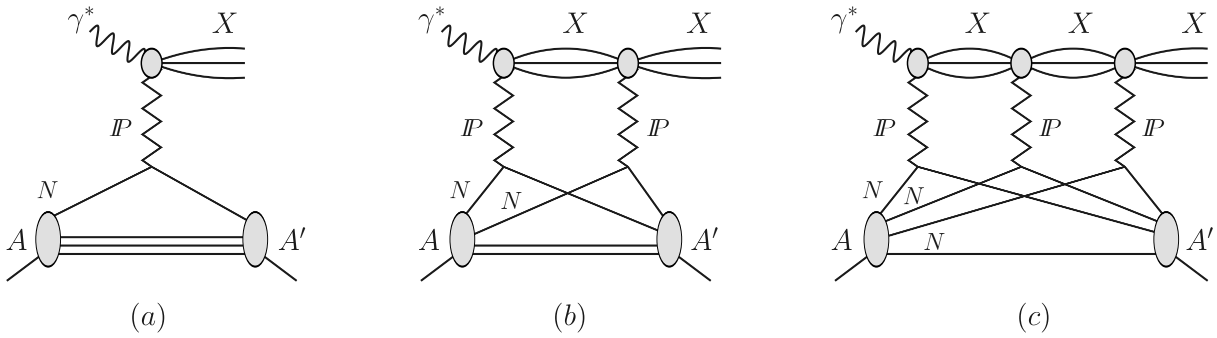
- Predicted to be:
    - $R_{\mathrm{diff/tot}} > 1$ due to nuclear enhancement of saturation scale $Q^2_{s,A}$, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303; Lappi, Le, Mäntysaari, PRD 108 (2023 114023
    - $R_{\mathrm{diff/tot}} < 1$ due to strong leading twist nuclear shadowing, Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255

Leading twist approach to nuclear shadowing

- Method to calculate various nuclear parton distributions (usual, generalized, diffractive) as input for DGLAP evolution, Frankfurt, Strikman, EPJ A5 (1999) 293; Frankfurt, Guzey, Strikman, Phys. Rept. 512 (2012) 255 → alternative to global fits of nPDFs.

- Based on:
  - Gribov-Glauber model of NS for soft hadron-nucleus scattering
  - QCD factorization theorems for inclusive and diffractive DIS.

- $\gamma^* + A \to X + A'$ amplitude is a series of diffractive scattering off $i = 1,2,\ldots,A$ target nucleons:



- Coherent diffraction $A' = A$:

$$\sigma_{\gamma^* A \to XA} = \int d^2\vec{b}\,|\Gamma_{\gamma^* A \to XA}(\vec{b})|^2 = 4\pi \frac{d\sigma_{\gamma^* N \to XN}(t=0)}{dt} \int d^2\vec{b} \left| \int dz \rho_A(\vec{b},z) e^{iz\Delta_{\gamma^* X}} e^{-\frac{1-i\eta}{2}\sigma_{\text{soft}} \int_z^\infty dz' \rho_A(\vec{b},z')} \right|^2$$

diffractive cross section on proton measured at HERA

nuclear density

model-dependent cross section

LTA to nuclear shadowing (2)

- Apply collinear QCD factorization for diffractive DIS, Collins, PRD 57 (1998); PRD 61 (2000) 019902 ⟶ from structure function to parton distributions:

$$f_{i/A}^{D(3)}(x, x_{I\!P}, Q^2) = 4\pi f_{i/p}^{D(4)}(x, x_{I\!P}, Q^2, t=0) \int d^2\vec{b} \left| \int dz \rho_A(\vec{b}, z) e^{izx_{I\!P}m_N} e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)\int_z^\infty dz' \rho_A(\vec{b},z')} \right|^2$$

$$= f_{i/p}^{D(3)}(x, x_{I\!P}, Q^2)\frac{1}{\sigma^i_{\rm el}(x)} \int d^2\vec{b} \left| 1 - e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)T_A(\vec{b})} \right|^2$$

$$\boxed{\begin{aligned} \sigma_{\rm el}(x) &= \frac{[\sigma_{\rm soft}(x)]^2}{16\pi B_{\rm diff}} \\ T_A(\vec{b}) &= \int dz \rho(\vec{b}, z) \end{aligned}}$$

- Transparent interpretation: nuclear diffractive PDFs shadowed in proportion to the nuclear elastic cross section.

- Similarly for quasi-elastic scattering using completeness final states A' :

$$\sigma_{\gamma^* A\to XA'} = \int d^2\vec{b}\, \langle A| \left|\Gamma_{\gamma^* A\to XA}(\vec{b})\right|^2 |A\rangle = \sigma_{\gamma^* N\to XN}\frac{1}{\sigma_{\rm el}} \int d^2\vec{b} \left(\left| 1 - e^{-\frac{1-i\eta}{2}\sigma_{\rm soft}T_A(\vec{b})} \right|^2 + e^{-\sigma_{\rm in}T_A(\vec{b})} - e^{-\sigma_{\rm soft}T_A(\vec{b})} \right)$$

$$\big\downarrow$$

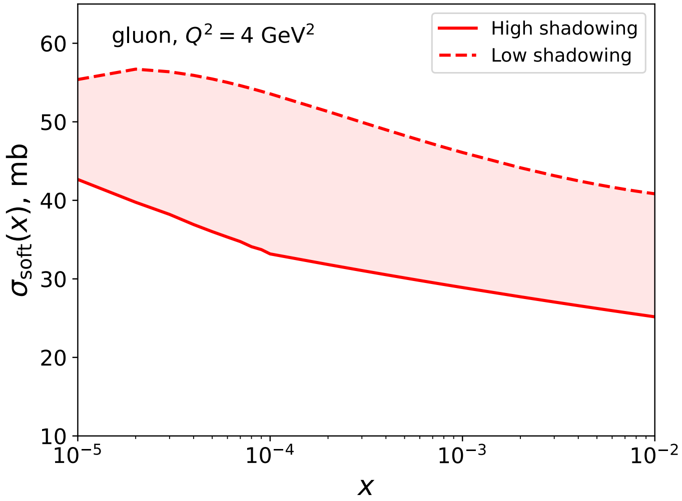
$$\tilde{f}_{i/A}^{D(3)}(x, x_{I\!P}, Q^2) = f_{i/p}^{D(3)}(x, x_{I\!P}, Q^2)\frac{1}{\sigma^i_{\rm el}(x)} \int d^2\vec{b} \left(\left| 1 - e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)T_A(\vec{b})} \right|^2 + e^{-\sigma^i_{\rm in}(x)T_A(\vec{b})} - e^{-\sigma^i_{\rm soft}(x)T_A(\vec{b})} \right)$$

$$\boxed{\sigma_{\rm in}(x) = \sigma_{\rm soft}(x) - \sigma_{\rm el}(x)}$$

- In this case, NS is given by sum of elastic and inelastic nuclear cross sections.

LTA predictions for nuclear diffractive PDFs

- Assumed that diffractive intermediate states X do not mix → one free parameter $\sigma^i_{\rm soft}(x)$ → controls size and uncertainties of LTA predictions.



- High shadowing: given by probability of diffraction

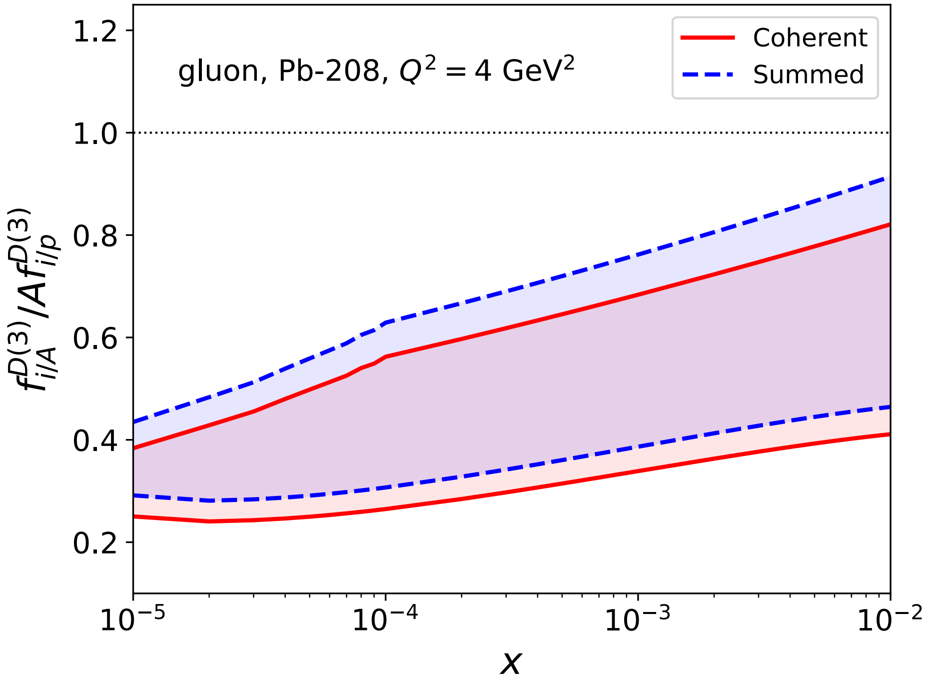
$$\sigma^i_{\rm soft}(x) \approx \sigma_2(x) \equiv \frac{16\pi}{f_{i/p}(x)} \int_x^{0.1} \frac{dx_{I\!P}}{x_{I\!P}} f^{D(4)}_{i/p}(x, x_{I\!P}, t=0)$$

- Low shadowing: calculated using model for hadronic structure of ρ meson.

- In LTA, nuclear shadowing driven by diffraction on proton → 10-15% probability of diffraction in DIS@HERA leads to large suppression of nuclear PDFs at small x.

- Compare to impulse approximation (IA):

$$\frac{f^{D(3)}_{i/A}}{A f^{D(3)}_{i/p}} = \frac{4\pi B_{\rm diff}}{A} \int d^2\vec{b}\,(T_A(\vec{b}))^2 = \frac{B_{\rm diff}}{A} \int dt F^2_A(t) = 4.3$$

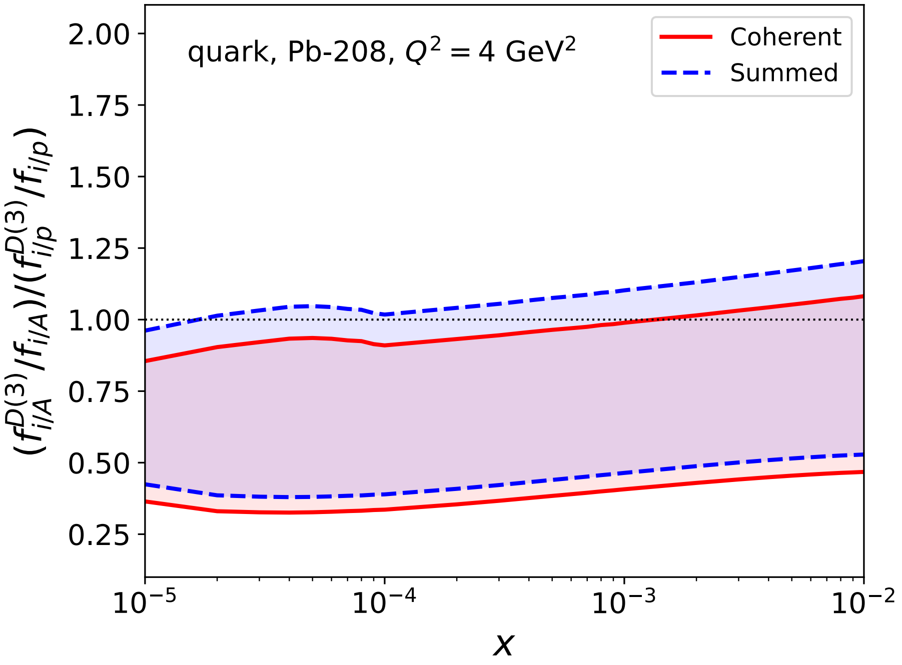


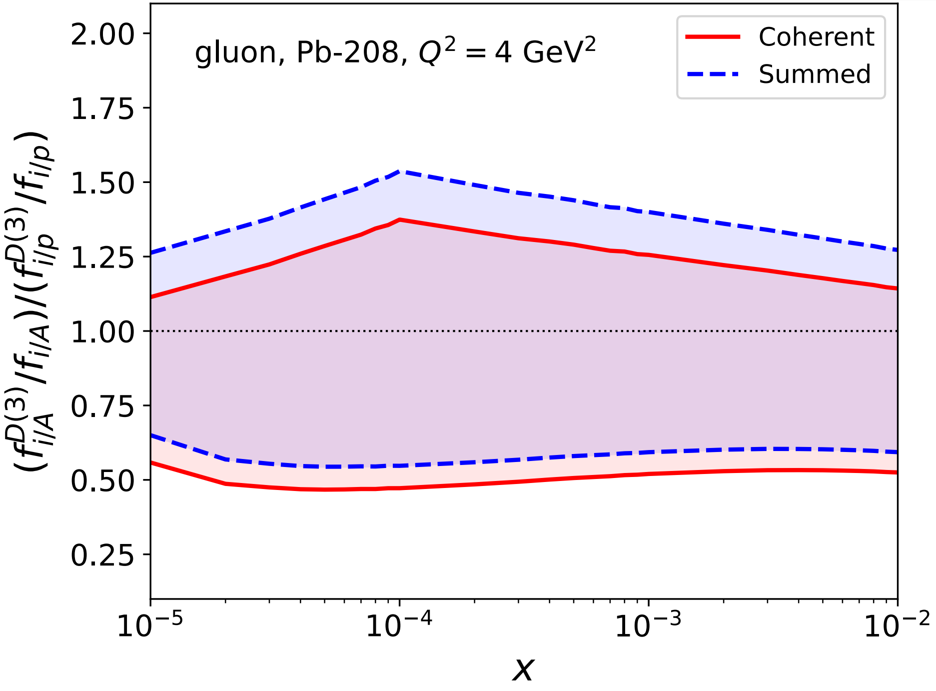
LTA predictions for R$_{\rm diff/tot}$

- Combine LTA predictions for diffractive and usual nuclear PDFs:

$$\frac{f_{i/A}^{D(3)}(x,x_{I\!P},Q^2)/f_{i/A}(x,Q^2)}{f_{i/p}^{D(3)}(x,x_{I\!P},Q^2)/f_{i/p}(x,Q^2)} = \frac{\sigma^i_{\rm soft}(x)}{\sigma^i_{\rm el}(x)} \frac{\int d^2\vec{b} \left|1-e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)T_A(\vec{b})}\right|^2}{2(1-\lambda^i(x))\Re e\int d^2\vec{b}\left(1-e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x)T_A(\vec{b})}\right)+\lambda^i(x)A\sigma^i_{\rm soft}(x)}$$

$$\boxed{\lambda^i(x) = 1-\sigma_2^i(x)/\sigma^i_{\rm soft}(x)}$$

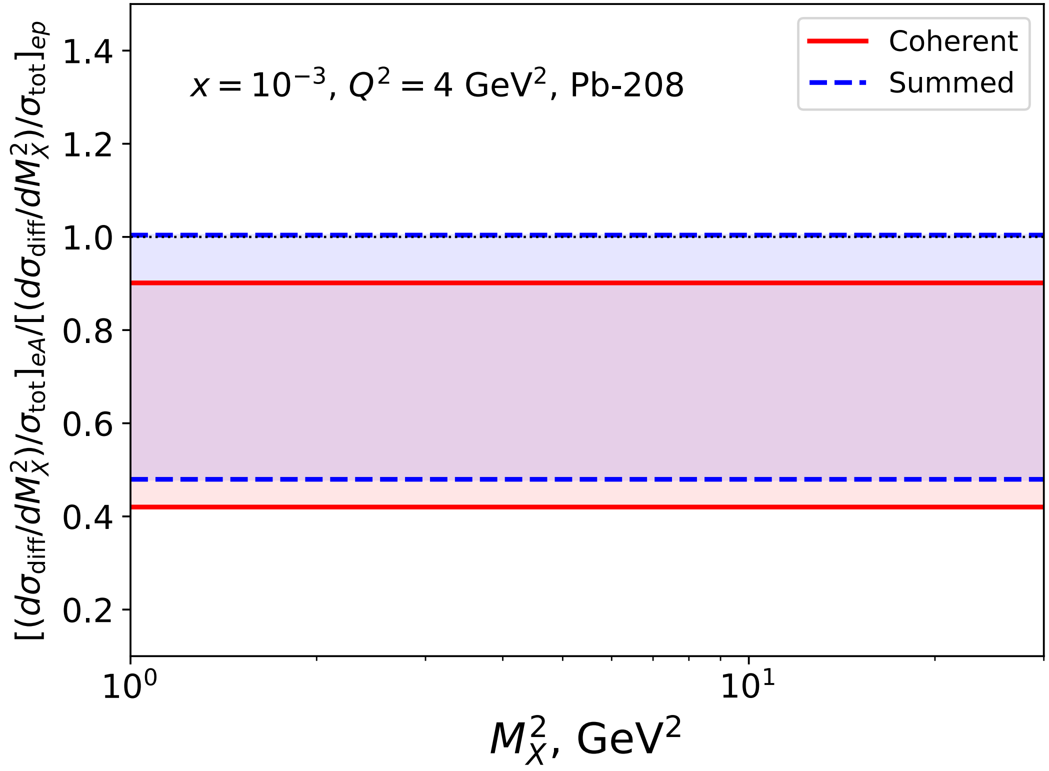




- Suppression $R_{\rm diff/tot} \approx 0.5-1$ (quarks) and $R_{\rm diff/tot} \approx 0.5-1.3$ (gluons) due to interplay of large leading twist nuclear shadowing for diffractive and usual nuclear PDFs.

LTA predictions for $R_{\mathrm{diff/tot}}$ (2)

- LTA predictions for the ratio of cross sections calculated at next-to-leading (NLO) of perturbative QCD as function of diffractive mass $M_X^2 = Q^2(x_{I\!P}/x - 1)$:



- Reaffirmed earlier LTA result $R_{\mathrm{diff/tot}} \approx 0.5 - 1$ and difference from nuclear enhancement $R_{\mathrm{diff/tot}} \approx 1.5 - 2$ in the gluon saturation framework, Kowalski, Lappi, Venugopalan, PRL 100 (2008) 022303; Lappi, Le, Mäntysaari, PRD 108 (2023) 114023.

- $R_{\mathrm{diff/tot}}$ is flat as function of M_X^2 due to assumed independence of $\sigma^i_{\mathrm{soft}}(x)$ on $x_{I\!P}$.

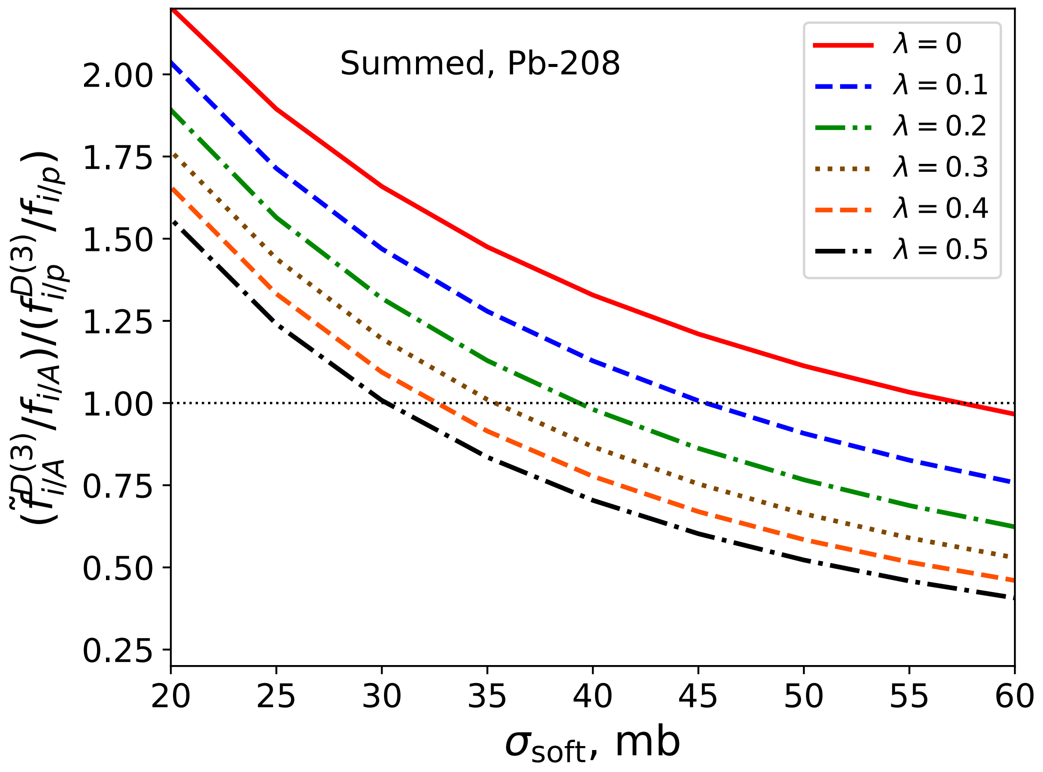
LTA predictions for R$_{\text{diff/tot}}$ (3)

- To understand these results and comparison with dipole model, examine $R_{\text{diff/tot}}$ as function of $\sigma^i_{\text{soft}}(x)$ and $\lambda^i(x) = 1 - \sigma^i_2(x)/\sigma^i_{\text{soft}}(x)$.

- Small $\sigma^i_{\text{soft}}(x)$: color transparency (IA), NS → 0 → $R_{\text{diff/tot}} \approx 5$

- $\sigma^i_{\text{soft}}(x) \sim \sigma_{\rho N} \approx 20 - 30$ mb: weak NS, $R_{\text{diff/tot}} \approx 1.5 - 2$ → corresponds to dipole model

- $\sigma^i_{\text{soft}}(x) \geq 40$ mb: full-fledged NS, $R_{\text{diff/tot}} \approx 0.5 - 1.3$, strong dependence on $\lambda^i(x)$ (probability of point-like configurations in proton)



- Boundary of LTA applicability is the black disk limit (BDL): $\sigma^i_{\text{soft}}(x) = \sigma^i_2(x) = 8\pi B_{\text{diff}} \approx 60$ mb, using $B_{\text{diff}} = 6\ \text{GeV}^{-2}$ measured at HERA.

- In BDL, $\lambda^i(x) = 0$ and $R_{\text{diff/tot}} \to 1$ and $R^{\text{coh}}_{\text{diff/tot}} \to 0.86$.

Leading twist nuclear shadowing and Q$_s$

- Heuristic definition of saturation scale through the b-dependent gluon density

$$\frac{Q^2_{sA}(b)}{Q^2_{sp}(b)} = \frac{g_A(x,b,Q^2)}{g_p(x,b,Q^2)} = \pi R_p^2 \left[\lambda^i(x) T_A(\vec{b}) + (1-\lambda^i(x)) \frac{2}{\sigma^i_{\rm soft}(x)} \Re e \left(1 - e^{-\frac{1-i\eta}{2}\sigma^i_{\rm soft}(x) T_A(\vec{b})} \right) \right]$$

- For nuclear PDFs, same parameters as before, but remove integration $\int d^2\vec{b}$

- For proton PDFs, Gaussian b-profile:

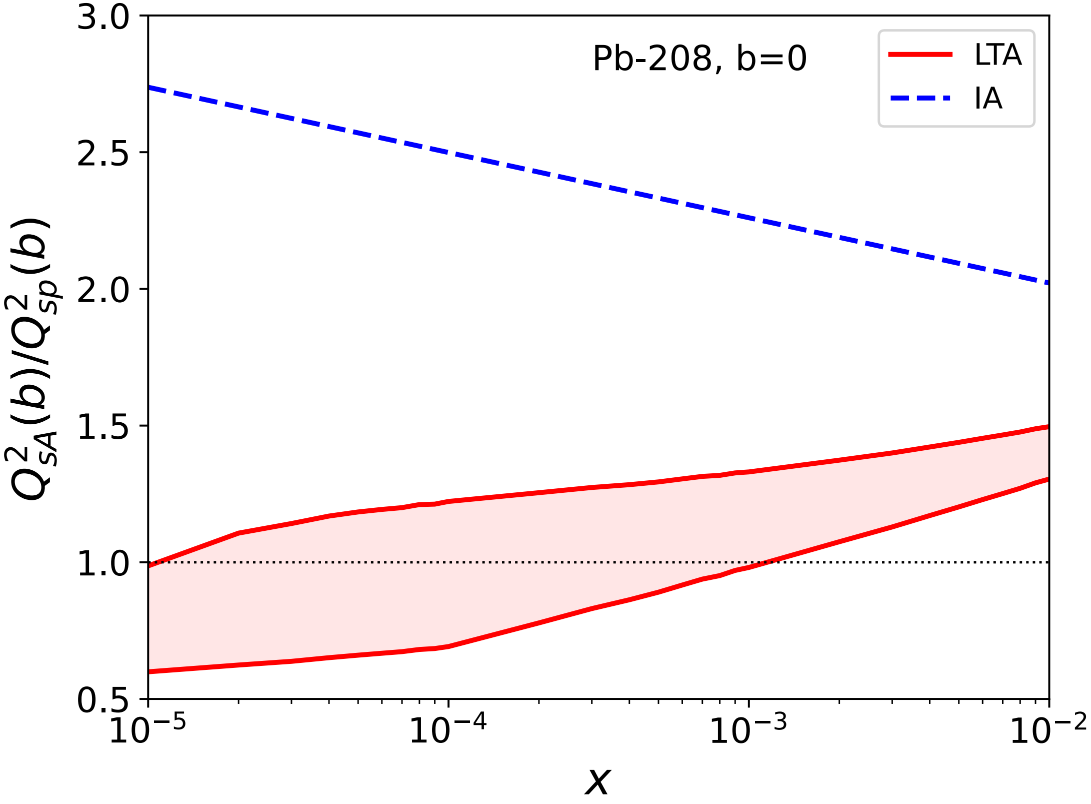
$$g_p(x,b,Q^2) = \frac{e^{-b^2/R_p^2}}{\pi R_p^2} g_p(x,Q^2)$$ with

$$R_p^2 = 2B_{J/\psi} = 9 + 0.4\ln(x_0/x)\ {\rm GeV}^{-2}$$

- In BDL: $$\boxed{\frac{Q^2_{sA}(b=0)}{Q^2_{sp}(b=0)} \approx \frac{2\pi R_p^2}{\sigma^i_{\rm soft}(x)} \sim 1}$$

- Neglecting leading twist shadowing (IA)

$$\frac{Q^2_{sA}(b)}{Q^2_{sp}(b)}_{|{\rm IA}} = \pi R_p^2\, T_A(\vec{b}) \sim A^{1/3}$$



→ $Q^2_{sA}/Q^2_{sp} \approx 1$ due to strong leading twist shadowing and dilute nuclear density.

Summary

- Competing mechanisms for high-energy (small x) hard scattering on nuclei.

- Ratio of the diffractive-to-total DIS cross sections for a heavy nucleus and proton at EIC discriminates between leading twist shadowing and saturation.

- We confirmed our result that $R_{\rm diff/tot} \approx 0.5 - 1.3$ due to strong leading twist shadowing in contrast with $R_{\rm diff/tot} \approx 1.5 - 2$ in the gluon saturation framework.

- $R_{\rm diff/tot}$ is controlled by the (dipole) cross section, which is large in LTA due to connection to diffraction on proton and small in the dipole model.

- One needs complementary observables/processes, e.g., the longitudinal nuclear structure function $F_L^A(x,Q^2)$, Frankfurt, Guzey, McDermott, Strikman, JHEP 02 (2002) 027, photoproduction of J/ψ in AA UPCs at LHC and RHIC, Guzey, Kryshen, Strikman, Zhalov, PLB 726 (2013) 290; Guzey, Strikman, 2404.17476 [hep-ph], vector meson/jet cross section ratios, Kovchegov, Sun, Tu, PRD 109 (2024) 094028.

- Leading twist nuclear shadowing as well as dilute nuclear density strongly deplete nuclear enhancement of the saturation scale $Q_{sA}^2/Q_{Sp}^2 \approx 1$.